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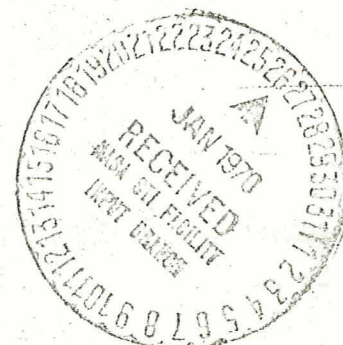
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RELATION OF AURORAL RADIATION
TO THE MAGNETOPAUSE
AND TO VAN ALLEN RADIATION*

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Abstract. A magnetospheric configuration is devised from consideration of experimental data combined with a mixture of intuition and a few theoretical concepts. It is proposed that the high-altitude islands, the third radiation zone, the skirt, cusp, neutral sheet and plasma sheet may all be regarded as constituents of an auroral-radiation domain. The domain is occupied by low-energy electrons and protons which show significant temporal variations under the occasional influence of non-adiabatic processes, and which particles may occasionally bombard the atmosphere to cause day time and night time auroras. The outer equatorial boundary of this domain at noon is taken to be the magnetopause, and the inner boundary of the auroral domain is deemed equivalent to the outer boundary of Van Allen radiation. During magnetically-quiet times, these boundaries are judged to be at geocentric radial distances (R_0) at noon of $\sim 10 R_E$ and $\sim 8 R_E$ respectively, with the inner edge fuzzy. During geomagnetic storms, the auroral domain can expand and the inner edge can advance to $\sim 3 R_E$ or less. This process is judged to accompany both the occurrence of low-latitude auroras and the non-adiabatic losses of Van Allen radiation formerly in the region. Magnetospheric models which have auroral acceleration on open magnetic field lines (cf. Dessler and Juday, 1965) or on field lines to the neutral-sheet only (cf. Speiser, 1965) are shown to have severe difficulties in meeting these and other specified requirements.

INTRODUCTION

It is the purpose of this note to present a magnetospheric model wherein we locate the source of auroral particles, and envisage the associated auroral domain to be the region that separates the magnetopause from the zone of stably-trapped Van Allen Radiation (Figure 1).

There has been considerable discussion about the source of the particles that bombard the atmosphere to cause auroras. It has been argued for some time that, if these particles ultimately had come from the sun, then the contrast between their interplanetary velocity of some 10^3 km/sec (calculated from the one-day delay between a large solar flare and a great world-wide aurora) and their velocity required to penetrate the atmosphere to auroral altitudes of ~ 100 km (a velocity of $\sim 10^5$ km/sec) necessitates a "local" or near-earth acceleration mechanism.

With satellites exploring terrestrial surroundings and with the discovery of Van Allen radiation [Van Allen, 1961], the collisionless bow shock [Ness, et al., 1964], the magnetopause [Bridge, et al., 1961; Cahill and Amazeen, 1963] and the extended magnetospheric tail, [Ness, et al., 1964] (Figure 1), one might imagine that the site and details of this local acceleration could be specified exactly, but this is not so. One of the specific problems is that auroras occur in the day as well as the night [Davis and DeWitt, 1963; Johnson, et al., 1966; O'Brien, 1964].

O'Brien, [1964] made simultaneous satellite-based measurements of Van Allen particles, of the particles that cause auroras, and of the auroral light that was emitted. From these measurements it was concluded that the night-time auroral zone is delineated by magnetic field lines that pass through the high-latitude boundary of trapping of Van Allen radiation. However, even if one observes particles mirroring at 100-km altitude one has no assurance that

they actually will bounce from hemisphere to hemisphere and drift around the world in longitude and be durably trapped, i.e. be Van Allen particles. Accordingly, O'Brien [1964] was unable to conclude experimentally whether the auroral zone was inside or outside the boundary of trapping or straddling it. However, in the model we suggest here (Figure 1), it is envisaged that the auroral zone is just outside the boundary of trapping and contiguous to it.

The configuration is sketched in Figure 1 and energetic charged particles are deemed to occupy only four distinctive domains:

A. The Van Allen (Trapped-radiation) Zone, where energetic particles can bounce in latitude and drift in longitude completely around the earth [Van Allen, 1963], and where all processes are approximately adiabatic;

B. The Auroral Domain, in which we include the regions at low altitudes where energetic charged particles bombard the atmosphere to cause auroras [O'Brien, 1964], and also the regions at high altitudes shown in Figure 1, thus incorporating the "skirt" [Freeman, 1964; Frank, 1965], the "cusp" [Anderson, 1965a], the "third radiation zone" [Gringauz, et al., 1962], the neutral sheet [Ness, et al., 1964], the plasma sheet [Bame, et al., 1966], "islands" [Anderson, 1965a], and spikes [McDiarmid and Burrows, 1965]. In this domain, the gradient of \vec{B} is small and the particle fluxes variable (cf. Figure 2). This region is characterized by the predominant occurrence of non-adiabatic processes;

C. The Magnetosheath, where solar-wind particles, having been thermalized at the collisionless shock front [Ness, et al., 1964] stream around the geomagnetic field, compressing and distorting it as shown in Figure 1.

D. Interplanetary Space, populated by the supersonic solar wind [Parker, 1958; Snyder and Neugebauer, 1964].

In specifying only four domains, there is no intention of indicating that characteristics of the energetic particles may not be different at different locations in the domain. For example, of course, the Van Allen domain contains particles with very different fluxes and spectra at different locations, but all are characterized by the fact that the particles bounce in latitude and drift in longitude around the earth. Similarly, in the auroral domain there may be differences in detail, but the region is characterized by electron and proton spectra such as are encountered in aurora, by active acceleration, by time-variable processes and by the inability to drift around the world.

THE AURORAL DOMAIN

When the noon magnetopause was discovered at a geocentric radial distance (R_o) of $\sim 10 R_E$ (where $R_E = 6370$ km), and when it was found to coincide with a decrease in the flux of energetic particles [Freeman, et al., 1963], it was generally assumed that it was the outer boundary of Van Allen radiation. By contrast, in the model of Figure 1, we locate this boundary at $R_o \sim 8 R_E$ during magnetically quiescent conditions, and at progressively smaller geocentric distances during geomagnetic storms.

We regard the region of $8 R_E \lesssim R_o \lesssim 10 R_E$ on the noon meridian as being the Auroral domain rather than the Van Allen zone because particles with either large or small equatorial pitch angles (α_o) in the region cannot drift completely around the world [Anderson, 1965a]. First it is seen (Figure 2) that in this region the gradient of the geomagnetic field becomes small and it may even reverse sign (see Cahill and Amazeen, 1962). Consequently the longitudinal drift of particles with large α_o (i.e. those mirroring at low latitudes) will be negligible and perhaps reversible [Anderson, 1965a]. Second, there will be an L-shell splitting [McIlwain, 1966a] so that particles with small values of α_o would tend to drift into the magnetospheric tail and be lost. Consequently, even though particles in this region may bounce in latitude and be quasi-trapped, their inability to drift in longitude completely around the earth makes them ineligible to be Van Allen particles. Instead, we label them auroral particles, with characteristically soft spectra and large temporal variations (cf. O'Brien, 1964; Frank, 1965; Freeman, 1964).

The inner boundary of this auroral domain will be fuzzy and will depend on energy, pitch angle and longitude. Furthermore, during large geomagnetic storms the edge will move inwards. This movement of the low-altitude boundary of the Van Allen zones and of the night-time visible auroras has been observed down to invariant

latitudes (Λ) of 45° and less. The geomagnetic field lines through this region are labelled with the McIlwain [1961] L-shell parameter of $L \sim 2$ so that they nominally extend out to a geocentric radial distance R_0 of only $\sim 2R_E$. By contrast, the magnetopause is not observed to move closer than $\sim 7R_E$ [Cahill and Amazeen, 1963]. Indeed, for it to be simply compressed in to $2 R_E$ would require a solar-wind pressure to be some fifteen thousand times the normal value.

At least one attempt has been made previously to resolve this discrepancy between the large movement of the low-altitude boundary of trapping and the comparatively small movement of the magnetopause. Akasofu [1963] sought to explain the effect as due to enhancement of the perennially-elusive ring-current particles. However, this approach requires extraordinarily large ring currents to move the boundary down below 55° , and 45° would appear to require a new approach.

The occurrence of low-latitude auroras also poses a problem for the magnetospheric model presented by Dessler and Juday [1965], where auroral radiation was deemed to be energized on open field lines as they touch the magnetopause. Low-latitude auroras would then require that more field lines be blown open into the polar cap while the magnetopause is appropriately compressed. As discussed above, such compression does not occur, and the ring-current dilation proposed by Akasofu [1963] does not appear to reconcile the model with the data.

We resolve this problem here simply by postulating that the auroral-radiation zone expands in towards the appropriate geocentric radial distance. The inward expansion of the auroral zone leads to a non-adiabatic loss of Van Allen radiation, and indeed we would equate the immediate outer boundary of Van Allen radiation essentially with the inward penetration of this region characterized by non-adiabatic effects occurring during the particular storm.

For example, when McIlwain [1966b] found that the April 18, 1965 geomagnetic storm caused (a) an adiabatic loss and then recovery of protons $40 \text{ Mev} \leq E_p \lesssim 110 \text{ Mev}$ at $L \lesssim 2.1$, but (b) a non-adiabatic loss and no recovery at $L \gtrsim 2.6$, we would estimate that the auroral zone on this occasion had advanced inwards to $L \sim 2.5$. We would expect that auroras would have occurred down to $\sim 50^\circ$ to 55° magnetic latitude during this storm. While we know of no visual observations during this storm, since K_p reached a maximum value of 8, we may crudely estimate that an aurora would have occurred at about $(55^\circ \pm 5^\circ)$ by reference to the statistical movement of auroras versus K_p (see Gartlein and Sprague, 1960).

We also consider that non-adiabatic processes are common and predominant in this auroral domain. Frank [1965] presented evidence for a "strong acceleration mechanism for energetic electrons in the local-day part of the magnetosphere". He found irregular and variable structure of the profiles of energetic electrons ($E_e \gtrsim 1.6 \text{ Mev}$) at higher latitudes between about 5° and the magnetopause, i.e., in what we have termed in Figure 1 the auroral domain. Since there is continuous particle precipitation and auroral light in the auroral zone $5 \lesssim L \lesssim 10$ [O'Brien, 1964] it seems that there must be continuously-active acceleration processes, and we regard these as a characteristic of the auroral domain. One may speculate (but not prove as yet) that plasma instabilities (cf. Scarf, et al., 1965) may provide such common acceleration and precipitation at day and night, while magnetospheric-field merging provides violent night-time effects (cf. Axford, 1966; Speiser, 1965).

Low-altitude measurements of precipitated electrons with $E_e \gtrsim 40 \text{ kev}$ [O'Brien 1962 and 1964] show that precipitation can occur down to comparably small L values, say $L \sim 2$, with such intensities as to empty the radiation zones (if they were unreplenished) in a few hours or less. But observations show that the intensity both of precipitated and of "trapped" 40 kev electrons

increases with increasing K_p [O'Brien, 1964; Freeman, 1964]. However, observations at high altitudes clearly demonstrated that non-adiabatic losses of high energy ($\gtrsim 1$ Mev) particles can occur to deep within the magnetosphere. Furthermore, Bailey and Pomerantz [1965] present convincing ionospheric evidence that Mev electrons formerly trapped at $4.5 \lesssim L \lesssim 6$ were actually precipitated into the atmosphere during the February 8, 1965 event. Thus we note that a "chronological sequence of electron intensity radial profiles demonstrates unequivocally the out-of-phase nature of the low- and high-energy electron replenishments in the outer radiation zone" [Frank, et al., 1964].

O'Brien [1962 and 1964] envisaged a "splash-catcher" concept to explain the positive correlation between the planetary magnetic disturbance index K_p and the fluxes of 50 kev electrons at geocentric radial distances of ~ 4 to $8 R_E$, and the positive correlation of K_p and the fluxes of such electrons being precipitated into the atmosphere in auroral regions. It was supposed that if auroral radiation and Van Allen radiation were related at all, it was only in that they had a common cause. Here we elaborate the concept as follows:

During large geomagnetic storms the inner edge of the auroral domain (and thus the outer edge of the Van Allen zone) moves to smaller geocentric radial distances as the domain thickens. As a consequence there is a non-adiabatic loss of many high-energy ($\gtrsim 1$ Mev) Van Allen particles in the region. However, accompanying this expansion of the auroral zone there is an enhancement in the fluxes of lower-energy (~ 1 to 100's of kev) particles because these fresh particles are energized in the auroral processes. When the storm is waning, a residue of these low-energy particles is left trapped as the auroral domain shrinks. Subsequent processes such as diffusion may then energize these "injected" particles to typical Van Allen higher energies.

The experimentally-observed behavior of radiation in the magnetosphere (e.g. see Frank, 1965; Freeman, 1964; McIlwain, 1966b) appears consistent with this concept.

It is relevant to note that this concept of an "auroral domain" is similar in many ways to the convective region shown by Axford and Hines [1961] before the magnetopause, the shock front and the magnetospheric tail were found experimentally. In this context, it is as well to emphasize that in this note we concentrate on the energetic-particle domains in the magnetosphere, rather than on the magnetospheric configuration itself. The latter, of course, is best mapped out by measurements of magnetic fields and plasmas rather than by using energetic particles as tracers.

TESTS OF THIS CONCEPT

Insofar as this model was devised explicitly to fit known experimental data, consistency with existing data is more a measure of its scope than of its validity. However, some additional tests have been made.

It is always interesting to review old experimental data in the light of newer ideas. We have thus reviewed the extensive observations of the aurora of November 27/28, 1959. In this period, Explorer VII equipped with two shielded geiger tubes made repeated passes over auroras and over a monochromatic (6300A) red arc [O'Brien, et al., 1960]. In the first pass about 4 hours after the sudden commencement, the peak count rate of the type 302 geiger tube occurred over a visible aurora at a magnetic latitude of about 55° , and the count rate at higher latitudes, where the peak was normally found, was essentially zero. During the remainder of the night the count rate decreased, and the peak intensity of the energetic electrons was observed above the 6300A arc, i.e. at the low-latitude edge of the visible auroral activity. While there was at the time likely a mistaken assignment of 40 kev electrons as the cause of the 302 count rate (it now seems most likely that it was due to \sim Mev electrons) the behavior seems consistent with the model envisaged here.

Detailed testing of this model against available data is proceeding. For example, we have compared particle and magnetometer data from Explorer 12 [Cahill and Patel, 1966; Frank, et al., 1966] with particle data from Injun 1 [Maehlum and O'Brien, 1963] for the large magnetic storm of October 28, 1961. Injun 1 at an altitude of 1000 km found the boundary of trapping at $L \sim 4$ to 6. Explorer 12 in the near-equatorial plane found the magnetopause at 62,000 km or $9.7 R_E$ for particles [Freeman, 1964] and about 60,000 km for the magnetic field [Cahill and Patel, 1966]. However, the particle data

also show considerable structure in to radial distances of about 40,000 km or $6.3 R_E$, and we equate the latter distance with the boundary of trapping, which is comparable to that found by Injun 1.

In adopting the model of Figure 1, we equate the low-altitude spikes of McDiarmid and Burrows [1965] with the high-altitude islands of Anderson, et al., [1965]. Furthermore, as discussed elsewhere, these fast-rise (\sim minutes) and slow-decay (\sim hours) enhancements of electrons with $E_e \gtrsim 40$ or 45 kev are associated with intense fluxes of low-energy electrons whose energy spectrum rapidly hardens (see Bame, et al., 1966; O'Brien, 1966). O'Brien and Laughlin [1962] measured such fluxes at ~ 1000 km altitude, with intensities sufficient to cause visible auroras. Thus we conclude that the high-latitude edge of the auroral zone may have multiple structures. Indeed multiple auroral arcs are observed, [Akasofu, et al., 1965] and multiple islands are observed in the equatorial plane [Anderson, 1965a].

The low-latitude edge of the auroral zone will also not be clearly delineated, and there is a "fuzzy" region as the flux of precipitated electrons gradually (i.e. with increasing Λ) increases until it reaches the flux of local quasi-trapped electrons (cf. Figures 9 and 10 of O'Brien and Taylor, 1964).

We have discussed elsewhere [O'Brien, 1966] the different acceleration mechanisms that may operate in the auroral domain, and here merely draw attention to the fact that both daytime and night-time processes are required.

With the discovery of the neutral sheet and the associated plasma [Ness, et al., 1964; Bame, et al., 1966] there has been considerable speculation that it forms the source of auroral particles. The energy spectra and particle characteristics are similar to those found in auroras, although one can show that it could sustain world-wide aurora for only a few minutes. But these treatments have concentrated mainly on night-time phenomena, and as direct

balloon and satellite-borne experiments demonstrate (e.g. Anderson, 1965b; O'Brien, 1964; Johnson, et al., 1966) there is appreciable auroral precipitation during the day, and indeed there have been studies of visible "daytime" auroras [Davis and DeWitt, 1963]. If the neutral sheet is to be the source of such particles then the field lines must be open and must reach the neutral sheet some 10^6 km from the earth (cf. Dessler and Juday, 1965). Such an "open" configuration poses two distinct problems for dayside precipitation, viz. low-latitude precipitation without excessive compression of the magnetopause (see above) and also the rapid temporal variations of occasional electron precipitation (e.g. 0.2 sec as seen by Anderson, 1965b). (Note that an electron with 50 kev would take ~10 seconds to travel from the neutral sheet to the dayside atmosphere.)

We therefore consider it more reasonable to regard the dayside auroral domain as shown in Figure 1. This implies that acceleration mechanisms other than those associated with a neutral sheet should exist.

Another comparative test of the model proposed here and of the model envisaged by Dessler and Juday [1965] is given by the high-altitude spatial distribution of "auroral" particles in the geomagnetic tail at $\sim 15 R_E$. In Dessler and Juday's [1965] model, the radiation should have a theta (θ) configuration, where the bar of the theta is coincident with the neutral sheet, and where the periphery is found just inside the magnetopause, since the field lines from the auroral zone are all deemed to be "open". In our model sketched in Figure 1, we expect such radiation only in the plasma sheet, i.e. the bar of the theta. Preliminary data from the Vela satellites show that such radiation is indeed confined to the plasma sheet [Bame and Coon, private communication] thus validating our Figure 1 in this aspect.

As the auroral zone initially expands towards the equator we expect that the zone of precipitation would initially extend from the former low-latitude boundary of the zone to the ultimate low-latitude boundary, due to initial loss of formerly trapped particles. Comparison of equatorial (e.g. Frank, 1965) and ionospheric data (e.g. Bailey and Pomerantz, 1965) would seem to indicate that this phase might persist for tens of minutes, and that it would be characterized by precipitated particles with energies above normal auroral energies. Subsequent auroral precipitation could take place over all of the zone or presumably it could be localized to small regions within the zone, moving potentially between the high- and low-latitude extremes. The above statement is derived, of course, not from any deep-seated understanding of the auroral acceleration processes but merely from the knowledge that this is the observed behavior of auroras (e.g. Akasofu, et al., 1965).

DISCUSSION

This note does not purport to solve the fundamental problems of the auroral acceleration mechanisms, nor to choose between plasma instabilities, magnetic-field merging, electrostatic acceleration or other phenomena. The purpose is simply to propose a magnetospheric configuration which appears to lend coherence to existing experimental data and which is consistent with observed phenomena insofar as it invokes:

(1) At low-altitudes

(a) the high-latitude boundary of trapping of Van Allen radiation coincides with the low-latitude boundary of the auroral zone, i.e. auroras occur just outside the boundary of trapping at day and night;

(b) the high-latitude boundary of the auroral zone will be sharply-delineated on the day-side but "fuzzy" with sporadic spikes on the night side. Occasionally the

actual intense auroras may be localized over only a fraction of the total zone but free to move across it;

(c) precipitation events will always be conjugate on the day-side but sometimes (e.g. with spikes) not conjugate on the night side. Geomagnetic control (alignment with L contours) will tend to be strongest on the low-latitude edge of the auroral domain.

(2) At high-altitudes

(a) the auroral domain is the zone where non-adiabatic loss processes predominantly can occur (so that high-energy Van Allen particles may be lost) occasionally down to $L \sim 2$ [McIlwain, 1966b; Frank, 1965] and where fresh acceleration processes can occur (so that the flux of low-energy, i.e. "auroral", particles can increase);

(b) the auroral domain expands radially inwards during geomagnetic disturbances, even while the magnetopause remains at $R_o \gtrsim 7 R_E$, and

(c) there may be very intense sporadic fluxes of auroral electrons localized in a narrow (few degrees wide) cone around \vec{B} on the night-side of the earth [O'Brien, 1966].

It is historically perhaps interesting to note that in the above scheme of things one may detect both a "leaky-bucket" model (for the period when the auroral zone is expanding inwards) and a "splash-catcher" model (when the auroral zone contracts to prestorm values). (See O'Brien, 1962 and 1964 for further discussion). It is also of historical interest to note that, some decades ago when only night-time auroras were discussed, it was considered troublesome to have the impinging solar plasma cause phenomena on the back-side of the earth, since it was conceptually easier to cause day-time effects. By contrast, if one invokes only neutral-sheet

acceleration processes (e.g., Speiser, 1965), it is troublesome to explain the undeniable daytime phenomena. But then if one tries to explain both dayside and night side phenomena with a single acceleration process (cf. Dessler and Juday, 1965) there are further inconsistencies with observation, as discussed above. In the magnetospheric configuration presented here, the approach has been taken that there is a continuously-active dayside and nightside acceleration mechanism probably operative on closed field lines, together with a cataclysmic acceleration process (e.g. perhaps field-line merging) that occurs only at night.

Finally, it may be noted that the model envisaged in Figure 1 is an adaptation of the "negligible-merging" model of Dessler and Juday [1965]. There are other and plausible magnetospheric models wherein geomagnetic field lines may merge with interplanetary field lines on the day-side and night-side (e.g. Dungey, 1961; Axford, et al., 1965), and our proposed configuration can be readily adapted by the reader to such rapid-merging models without change in any arguments we have advanced.

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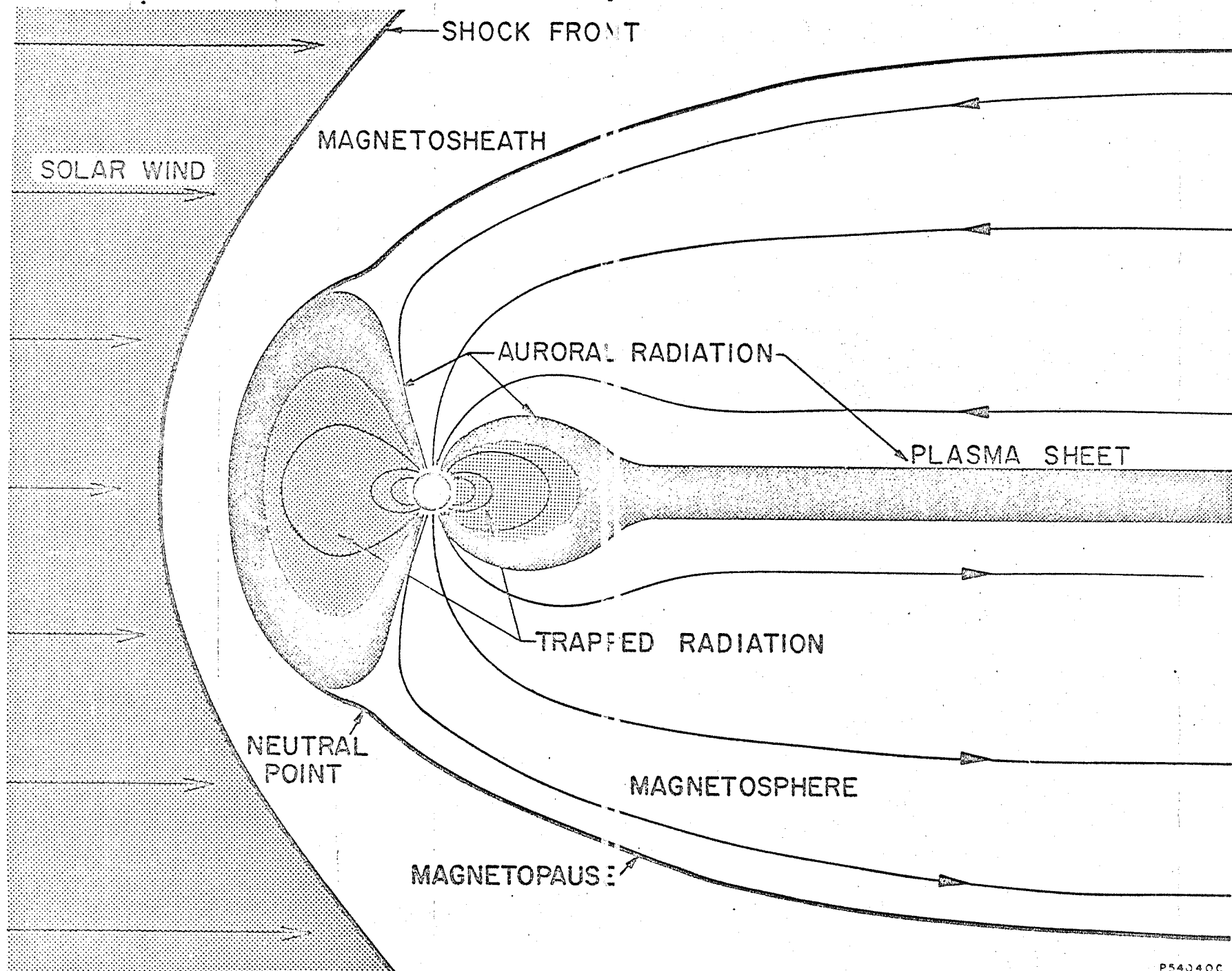
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FIGURE CAPTIONS

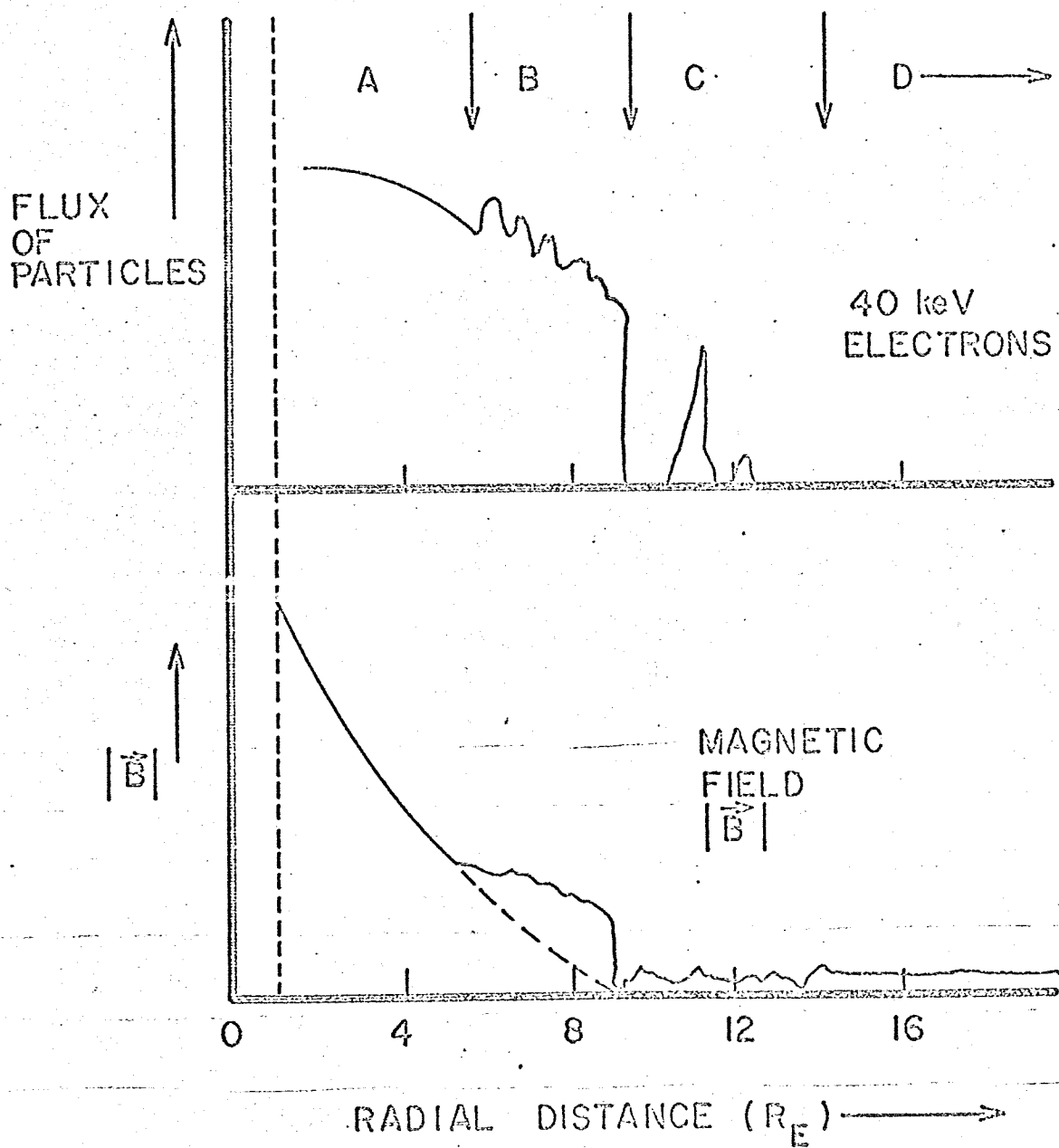
Figure 1: Magnetospheric configuration envisaged by O'Brien [1966].

The plasma sheet is also properly the auroral domain. This sketch is for a magnetosphere with negligible merging of geomagnetic and interplanetary magnetic fields. A "rapid merging" model would somewhat alter the appearance of this sketch but not materially modify its significance. Such features as the neutral points have never yet been seen.

Figure 2: Illustration of the energetic particle and magnetic-field characteristics regarded as typical of the noon meridian of the magnetosphere. Region A is occupied by relatively stable Van Allen radiation with a near-dipole field. Region B is the auroral domain, where particle fluxes are variable and grad B small. Regions C and D are the magnetosheath and interplanetary space respectively. Domain B expands inwards as A contracts during magnetic storms.



PARTICLE DOMAINS



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FIGURE 2